RETROSPECTIVELY TRIGGERED MRI OF ACTIVE OR PASSIVE JOINT MOTION

DESCRIPTION

The present technique relates to the magnetic resonance imaging of movable body parts. It finds particular application in conjunction with generating images of a joint in motion, and will be described with particular reference thereto. However, it is to be understood that it is also applicable to other movable body parts, such as the eyes and to autonomously moving body parts as well.

Heretofore, a wide range of cushions and joint positioning devices have been used to hold a subject frozen in a preselected physical position during magnetic resonance imaging. These joint positioning devices were effective to hold the patient against motion during the data acquisition time to eliminate the blurring and other image degradation attributable to patient motion.

When imaging a patient's joints, it is often advantageous to have images of the joint at different degrees of flexation. This was typically done by fixing the joint position and generating a first image. Then, the subject was repositioned with the joint in a different degree of flexation, the position was fixed, and another image was generated. Any number of still images with different degrees of flexation could be generated. US 5,899,859 to Votruba discloses an apparatus for stepping a joint to each of a plurality of predetermined positions and holding the joint still at each position while an MRI image is generated. This series of still images could be displayed sequentially to give the appearance of motion. Although the sequence of images might give the appearance of motion or even continuous motion, they are not images of the joint in motion.

The present application contemplates a new and improved method and apparatus which overcomes the above-referenced problems and others.

In accordance with one aspect of the present invention, a system is disclosed for generating cine images of a continuously moving bodily structure. A magnetic resonance imager generates magnetic resonance image data of a bodily structure of a

subject in an examination region as the subject moves through a series of kinematic motion studies. A means provides indications of current motion states through which the bodily structure is moving. A distributing means distributes the magnetic resonance data in accordance with the detected current motion states.

In accordance with another aspect of the present invention, a method is provided for generating cine images of a continuously moving bodily structure. The bodily structure continuously moves back and forth through a series of motion states. Magnetic resonance image data of the bodily structure is generated as it moves continuously through the motion states. Current motion states through which the joint is moving are detected. The magnetic resonance data is distributed in accordance with the detected current motion states.

One advantage of the present invention is that it images bodily structures, such as joints, while in dynamic motion.

Another advantage of the present invention resides in efficiently collecting data for a series of high resolution images.

Other advantages of the present invention include that it can be used for musculo-skeletal studies of a wide range of joints in a variety of magnetic resonance scanning devices.

Still further advantages and benefits of the present invention will become apparent to those of ordinary skill in the art upon reading and understanding the following detailed description of the preferred embodiments.

The invention may take form in various components and arrangements of components, and in various steps and arrangements of steps. The FIGURE is only for purpose of illustrating the preferred embodiments and is not to be construed as limiting the invention.

The FIGURE is a diagrammatic illustration of a magnetic resonance imaging system in accordance with the present invention.

With reference to the FIGURE, a magnetic resonance scanner **10** includes a main magnet for generating a temporally constant B_0 magnetic field through an imaging region **12**. The scanner further includes gradient magnetic field coils for generating magnetic field gradients across the imaging region and radio frequency coils for exciting and manipulating resonance in a region of interest of a subject in the examination region and receiving the resultant resonance signals. In one embodiment, a kinematic joint device **14** for moving kinematic studies is mounted to a subject support **16** and disposed in the examination region. The kinematic joint device is strapped or otherwise connected with a patient adjacent a joint to be imaged, positioning the joint preferably at the isocenter of the MR scanner. The kinematic joint device is configured to permit the joint to be flexed, but only along a preselected trajectory. The kinematic joint device can limit the kinematic motion to a plane; can limit motion to rotation along a preselected arc, or the like.

In the illustrated embodiment, the kinematic joint device includes a first portion **20** for fixing a subject's thigh at a preselected, fixed angle to the patient support **16.** A second portion **22** which is pivotally connected to the first portion is configured to receive the patient's calf. A pivotal connection between the two portions permits the subject to move the calf up and down along a preselected trajectory, e.g., within a vertical plane. Of course, various other devices as are known in the art can be used for limiting the motion of knees and other joints.

Alternately, the joint or other movable bodily structure is moved over the selected trajectory without mechanical assistance. The eyeball, for example, is not well suited for interconnection with a mechanical device, nor are most internal organs.

A sequence controller **30** controls a series of gradient coil amplifiers **32** and a transmitter **34** to initiate a selected imaging sequence, preferably a three-dimensional, high resolution gradient echo sequence. Such a sequence typically generates a line of data in 6-10 milliseconds. The sequence controller causes the imaging sequence to be applied repeatedly as the subject moves the bodily structure repeatedly over the selected trajectory. A receiver **36**, which is connected with receive coils either mounted in the scanner or positioned on the joint as localized coils, demodulates resonance signals to generate a data line with each repetition of the imaging sequence. As is typical in the art, data lines which are phase encoded to span k-space are generated.

A motion state indicator means **38**, such as an angular position resolver in the kinematic joint device embodiment detects the instantaneous kinematic state of the bodily structure and outputs a signal indicative of the current motion state. Other motion state indicator means are also contemplated such as electro-mechanical devices for sensing linear movement, cameras, laser gauges, MR navigator echoes, and the like. A kinematic motion state circuit **40** converts the output of the motion state indicating means into an appropriate indication of the current kinematic state of the joint as each data line is read. Each data line with its kinematic state information is conveyed to a processor or data distributing means **42** for selecting and distributing the data lines according to motion state and assigning the selected data lines to a plurality of cine image data sets. Any data collected for motion states that are not along the selected trajectory, or are otherwise identified as being inappropriate to the study, are discarded. These k-space data sets are stored in corresponding memory sections **44** of one or a plurality of image data memories. Optionally, a one-dimensional inverse Fourier transform is performed on each data line before it is stored in the data memory **44**. More specifically to the illustrated knee joint embodiment, the range of kinematic motion is divided into a plurality of arc segments, preferably equal arc segments. As the patient flexes the joint continuously over the range of motion, kinematic data lines which are generated. The motion state indicating means **38** indicates the current arc segment window through which the subject is moving and the current window and the data lines are stored in a corresponding data window subset of the data memory **44**. Preferably, the arc segments for the centrally phase-encoded views are relatively small, with the arc segments for the peripheral phase-encoded views being larger. The subject flexes the joint back and forth over the motion range. As may be appropriate to the study, data lines are generated either during both back and forth motion or only during motion in one direction.

Various distributing techniques are contemplated. In one embodiment, the arc segment windows are defined based on physical motion segments along the trajectory and the data acquisition continues until a full data set is collected in the window for each motion state. Optionally, a data line memory **46** keeps a record of the phase encode steps for which data lines have been collected for each motion window. The sequence controller **30** adjusts the phase encoding order to generate data lines with needed phase encoding in the various motion segments. As another option, the data distributing means makes a "best

fit" division of the data lines among the windows, with the fit parameters being stricter for centrally phase encoded data lines and progressively looser for higher phase encodings. Alternately, the higher phase encoded data lines can be distributed into two or more adjacent motion state windows. Further, data lines can be replaced by newly acquired data to improve the fit with which the data lines are matched to the motion states. Numerous other distributing techniques are also contemplated. For example, rather than fixing the range of motion corresponding to each window, the minimum amount of data per window can be specified. When data in excess of the minimum is collected, the window can be divided into two or more new windows corresponding to smaller ranges of motion and the data redistributed.

Once the set of k-space data lines for each of the motion segments has been collected, preferably three-dimensional data sets, a reconstruction processor **50** reconstructs each data set into a corresponding image, preferably a 3D image, which is stored in sections of an image memory **52**. A video processor **54** withdraws selected portions of the 3D images for display on a video monitor **56**. Preferably, the video processor includes a cine processor **58** which withdraws corresponding images sequentially from each of the motion state images to produce a moving or cine display of the joint motion. The displayed cine images may be slice images, 3D renderings, or other image representations as are known in the art. The various tissues can be displayed with different coloration, with some tissue removed or invisible, e.g., with the bones transparent to view the cartilage, muscle, patella, meniscal fluid, other soft tissue directly, and the like. Reference information such as central axes of bones, highlighted surface contours, radius of curvature, dimensions, and the like can be superimposed on the images.

In a real time acquisition mode, the central data lines are collected first with data collection moving from the center of k-space progressively outward. Optionally, peripheral portions of k-space are zero-filled until actual data is collected. The reconstruction processor continuously or semi-continuously updates the reconstructed images as more data is collected. The displayed images improve in resolution and detail in real time as more data is collected. The operator can terminate the scan when images of a satisfactory quality for the current diagnostic purposes have been generated.

Optionally, a half-Fourier processor uses conjugate symmetry to create synthetic data lines on the opposite side of the centrally encoded data lines for each actually collected data line.

As another option, a receive coil **60** that has multiple antennae for parallel imaging, such as a SENSE coil, can be used to collect data in fewer repetitions. The SENSE coil can be attached to or adjacent the region of interest to move with it or can be stationarily mounted to the scanner. To compensate for changes in sensitivity characteristics of the antennae with motion state, low resolution, central k-space reference data are generated for each motion state and stored in reference data memories **62**. The reference data sets are used to generate an inversion matrix for each motion state window which are used to unfold aliased parallel images into unaliased images. In a preferred embodiment, the continuous motion data is undersampled, and the reference data is used as a regularization image to improve the conditioning of the matrix inversion. Optionally, the reference and continuous motion data can be generated with different contrasts to create related images with different contrasts for emphasizing a selected tissue.

As an additional option, multiple scans with different MR contrasts (e.g., T_1, T_2, steady-state free precession, water-only) are acquired to improve the diagnostic value of the examination.. In that case, it is preferred to acquire the reference data for all relevant motion states only once, in a separate, specifically tailored scan.

Rather than the patient flexing the joint freely through the motion states, a pneumatic cylinder **70** or other resistance means is optionally provided to provide a selectable force against which the patient must work to flex the joint.

In yet another alternate embodiment, the sequence control circuit **30** is connected with a controller **72**, such as pneumatic controller, which controls the pneumatic cylinder **72** or other motor means to control the movement of the kinematic motion device. In this manner, the sequence control means can control the motion state dynamically to move the joint continuously through the range of motion. Because the sequence controller is both controlling the continuous motion and the phase encoding, it optimizes the efficiency with which the phase encoding data for each of the motion range windows is generated. By knowing the position which the joint will be in before the phase encoding is applied, the sequence controller can select only phase encoding steps which are needed for the window that the joint will be in when the data line is generated and eliminate the

collection of redundant or superfluous data. Further, more centrally phase encoded data lines can be generated nearest the centers of the windows.

In yet another alternate embodiment, the motion state indicator circuit **40** is connected with a triggering means **74** which triggers or steps the sequence controller **30** to apply the appropriate phase encoding to collect k-space data lines that are needed in the kinematic motion state window in the current state of motion. The triggering means **74** and the sequence controller **30** interact with the view memory **46** to determine the phase encode steps which are still needed for each motion state window as it is entered.

The invention has been described with reference to the preferred embodiments. Modifications and alterations will occur to others upon a reading and understanding of the preceding detailed description. It is intended that the invention be construed as including all such modifications and alterations insofar as they come within the scope of the appended claims or the equivalents thereof.